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DIGITAL CHARACTERIZATION OF RECOIL CHARGED-PARTICLE TRACKS FOR NEUTRON MEASUREMENTS[1]

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Abstract

We are developing a new optical ionization detector for imaging the track of a charged neutron-recoil particle in a gas. Electrons produced in the path of the recoil particle are excited by an external, high-voltage, RF, electric field of short duration. Their oscillatory motion causes ionization and excitation of nearby gas molecules, which then emit light in subsequent de-excitation. Two digital cameras image the optical radiation across two perpendicular planes and analyze it for the numbers of electrons in various volume elements along the track. These numbers constitute the digital characterization of the track. This information can then be used to infer the energy deposited in the track and the track LET in the gas. We have now observed alpha-particle tracks in a chamber utilizing these principles. The application of such a device for neutron dosimetry and neutron spectrometry will be described.

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1. Introduction

This paper is about a new approach to making neutron measurements. Neutrons are important in a wide variety of activities, ranging from basic nuclear physics to industrial and medical applications. In many installations, neutrons present unwanted problems, such as the direct exposure of personnel and the activation of equipment and structural materials. Such problems exist, for example, at many accelerator facilities. The work presented here grew out of the need for improved monitoring and dosimetry for persons occupationally exposed to neutrons.

2. Statement of the Problem

Given a neutron field, knowing the fluence rate as a function of neutron energy and solid angle at every point in space and time would, in principle, provide sufficient information about the neutrons for all practical purposes. The data would provide directly, for example, scattering cross sections in an experiment with a parallel beam of monoenergetic neutrons. For dosimetry, the data could be used to calculate, and thus determine indirectly, the absorbed dose or energy deposited per unit mass in tissue exposed to the neutron field. In fact, knowledge about the secondary recoil charged particles produced by the neutrons in tissue is of more direct relevance for dosimetry, as presently practiced, than knowledge about the neutron field itself.

For radiation protection purposes, regulations specify that one evaluate the dose equivalent to a person exposed to radiation. This quantity is the product of the absorbed dose (energy absorbed per unit mass) and the appropriate quality factor for the radiation. The latter is defined in terms of the linear energy transfer (LET) of an incident or recoil charged particle in water [1]. Unfortunately, no general solution exists for the technical problem of determining the energy deposited and LET of recoil events in tissue exposed to a neutron field. While there are definite successes, many aspects of neutron dosimetry remain an art.

3. Ionization Methods

Neutrons can be detected in a number of ways. Slow neutrons ($\lesssim$ 0.5 eV) can activate foils and, when absorbed by a nucleus, can produce energy-releasing reactions, such as $^{10}B(n,\alpha)^{7}Li$, which can be readily detected in a scintillator or proportional counter. Intermediate (up to ~ 0.1 MeV) and fast ($\gtrsim$ 0.1 MeV) neutrons produce, through elastic scattering, charged recoil particles that can be monitored with proportional counters. They also activate foils, typically selected with certain thresholds to provide neutron spectral information. Intermediate and fast neutrons can also be moderated first and then detected as slow or thermal neutrons by capture reactions.

Neutrons show a variety of interactions, and their cross sections are notoriously energy dependent. Of the two quantities required for dosimetry - the absorbed energy and the LET (or quality factor) - the former is more accessible to direct measurement. For example, a proportional-counter probe can be made with tissue-equivalent plastic walls enclosing a tissue-equivalent gas. If the wall thickness allows for secondary charged-particle equilibrium with the gas, and if other conditions of the Bragg-Gray principle are met, then the neutron dose in the walls can be obtained simply by measuring the pulse-height spectrum from the gas ionization.

Ionization in a gas provides a very sensitive and versatile process for radiation detection and dose measurement, and it is the basis for the digital approach, which we describe next.

4. The Digital Approach

Figure 1(a) shows the calculated track of a 1-MeV proton traversing a cylindrical volume, representing the probe of a proportional counter. The cylinder has a diameter of 5 cm and a length of 8 cm, and the track is in a plane containing the cylinder axis. The proton could have been produced under Bragg-Gray conditions in a wall surrounding the cylinder. The dots show the positions of the subexcitation electrons produced directly by the proton or one of its secondaries immediately after passage through the counter, before the electrons have drifted appreciably. Figure 1(b) shows the track of a 22-keV carbon ion entering the gas from the wall. This track is also in a plane containing the axis of the cylinder. As described in the caption, the two events, (a) and (b), produce about the same number of electrons. However, the carbon ion expends more energy than the proton, because of its higher W value (average energy per ion pair) as it stops. Operated as a proportional counter, this dosimeter would register comparable pulse heights from the two events, implying comparable doses. Also, the measurements would not indicate what quality factors should be assigned to the events. The calculations show that the average LET for this proton track segment is 200 MeV cm^2/g, for which a quality factor $Q \cong 4$ is appropriate. The LET for the C recoil is 1200 MeV cm^2/g, corresponding to $Q \cong 18$. The missing piece of information about neutron recoil events in a proportional counter is the track length in the gas.

Several approaches beyond this point have been proposed. H. H. Rossi pioneered the use of spherical proportional counters to measure LET spectra [2]. The isotropic chord-length distribution in the sphere is a simple analytic function, and one can statistically relate an event size with a track length. However, if a significant fraction of the recoil particles stop or start within the chamber, the track-length distribution will not be well approximated by the chord-length distribution. We devoted considerable effort to an iterative unfolding of LET spectra for a standard, cylindrical proportional counter, for which the chord-length distribution can be compiled numerically [2]. These methods have met with some success for energetic neutrons, but they still fall short of giving sufficiently accurate LET distributions in many cases. Position-sensitive proportional counters are also available, but they are sophisticated and costly for dosimetric purposes. On the other end of the spectrum, completely analogue "rem meters" exist to obtain neutron dose equivalent directly. However, their response is only approximate and is tied explicitly to currently defined quality factors.

At this point, we can ask a very fundamental question: What is the <u>most</u> information that one can have about a particle track in a gas? The particle leaves a number of subexcitation electrons, excited molecules, and positive ions in its wake. Short of knowing everything about a track, one can still learn a great deal by measuring the numbers of electrons in various volume elements spanning a chamber volume. In this fashion, a particle track would be characterized digitally as a set of integers, each associated with a given volume element of the chamber and providing the number of electrons in that element.

For dosimetry, the total number of electrons in tracks such as those in Fig. 1 would provide the absorbed energy, since the W values are known. Moreover, knowledge of the specific volume elements which contain electrons would enable the track length to be determined. The LET is then the ratio of the energy absorbed and the track length.

5. An Optical Electron Detection Technique

The most promising principle for obtaining digital data from tracks appears to be the detection of optical radiation from gas molecules excited in the immediate vicinity of the electrons in a track [3]. The operation of this detector can be understood from Fig. 2, which gives a schematic representation of the initial device we have built and used to see tracks from a ^{241}Am source, which emits 5.5-MeV alpha particles. Immediately after passage of an alpha particle, electrons in the track are excited by application of an external, high-frequency, high-voltage pulse applied across two parallel disc electrodes with the track between. The RF field causes the electrons to oscillate rapidly, gaining sufficient energy to ionize and excite the gas molecules in their immediate vicinity. The duration of the pulse is limited so that an avalanche onset does not occur. The excited gas molecules produce copious numbers of photons by fast fluorescent decay. The intensity of the light from different regions is proportional to the number of electrons there. The alpha-particle tracks can be readily seen by the naked, dark-adapted eye. Figure 3 shows a photograph of an alpha-particle track in the device.

The cylindrical chamber in Fig. 2 is about 3 cm in height and 10 cm in diameter. It was operated at pressures between 300 and 600 torr with various gases and mixtures, such as N_2, Ar, Ar + N_2, Ar + Xe, and Ar + TMAE [tetrakis (dimethylamine) ethylene]. A potential difference of ~10 kV was used at an operating frequency of 5-15 MHz and a pulse repetition rate of ~100 Hz. The best spatial resolution was visually judged to be about 1-2 mm in the direction perpendicular to that of the applied field and about 2-4 mm parallel to the field. The light intensity is highly dependent on gas composition and pressure as well as the voltage level of the RF pulse. Calculations confirm our observation that operation of the detector with small percentages (1-5%) of Xe or N_2 in Ar gives the best performance in terms of spatial resolution and light output from the track.

In going from this initial "proof-of-principle" device to a useful dosimeter or other device, a considerable amount of additional work remains to be done. For example, a triggering device is needed to turn on the field in response to the entrance of a particle, e.g. by using the natural fluorescence of the gas. Fast switching circuitry and triggerable RF voltage pulses of higher frequency and longer length must be developed. We also need to explore methods of limiting electron diffusion (e.g., by negative-ion formation), particularly at low pressures. The output itself requires computer hardware and software to record the track images and analyze them to extract the required information. We are investigating the use of two digital cameras to simultaneously scan and image the emitted light across two perpendicular planes outside the chamber. We developed an algorithm to unfold the digital data from an earlier version of the chamber and showed that it worked very successfully for determining dose and dose equivalent for neutron dosimetry [4]. In the longer term, we need to understand the basic physical processes and energy pathways that determine how the detector operates in order to optimize and fully utilize it.

An important characteristic of the device represented in Fig. 2 is that major variables, such as gas composition and pressure, RF pulse amplitude, frequency and duration, can be controlled externally and hence changing them does not require rebuilding a chamber.

Summary

We have described a digital concept for particle-track characterization and a prototype device that has demonstrated the needed track visualization. This basic approach has the potential for a variety of uses in addition to neutron dosimetry. One could make measurements of range and energy-loss straggling. Track-structure calculations could be checked experimentally. W values and Fano factors could be obtained on a track-by-track basis. Its potential as a neutron spectrometer has yet to be explored. Such a device could also be considered for 3-dimensional imaging of laser and X-ray beams.

References

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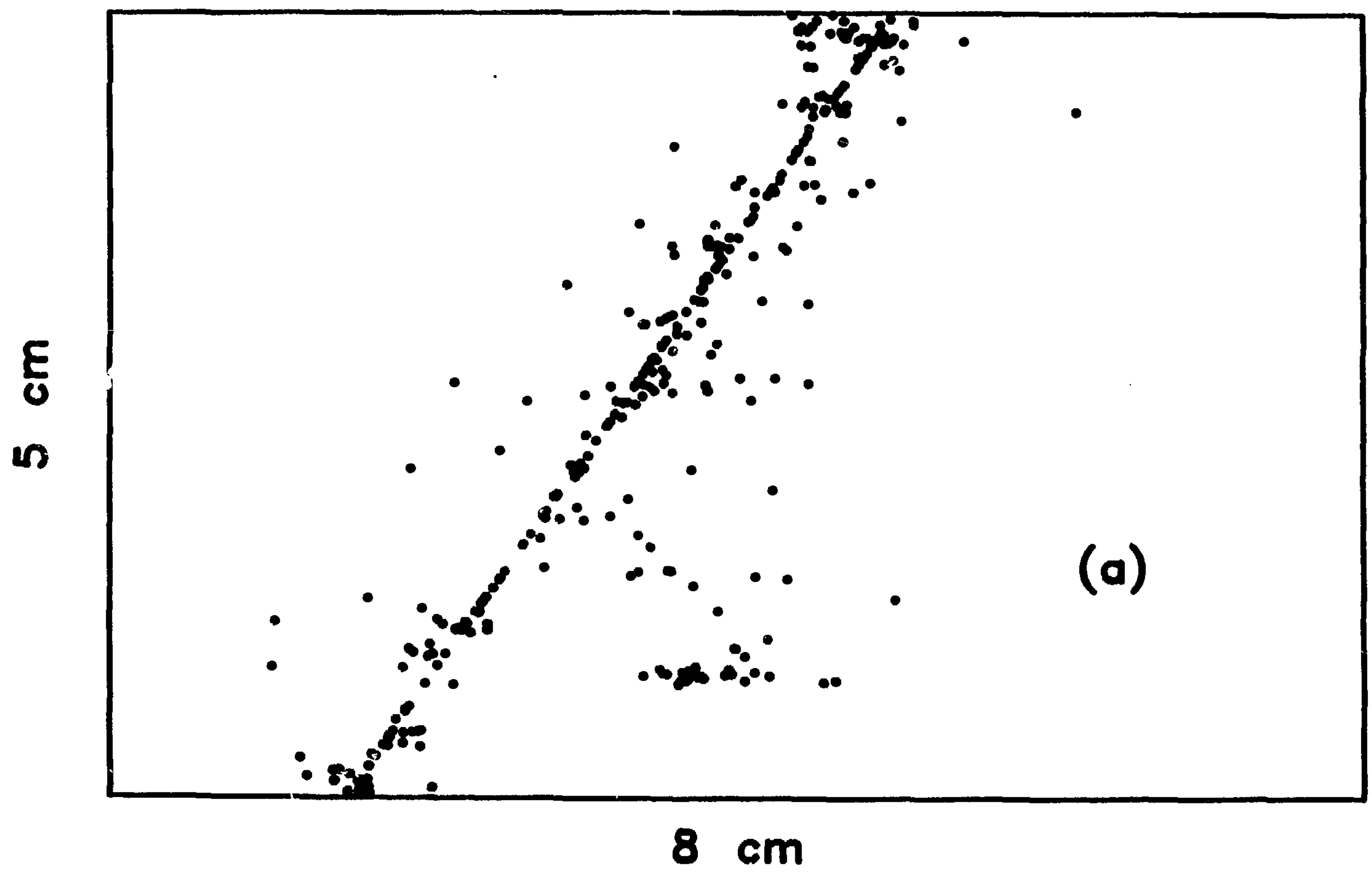
Fig. 1. (a) Calculated track of a 1-MeV proton crossing a Bragg-Gray chamber filled with CH_4 at 5 torr. This track produced 352 electrons, each represented by a dot. The proton lost 10.4 keV in the gas.

(b) A 22-keV carbon recoil ion from the wall of the same chamber. It produces 341 electrons and stops in the gas.

Fig. 2. Schematic diagram of initial device in which alpha-particle tracks can be seen.

Fig. 3. Digitally enhanced photograph of alpha-particle track in chamber, showing the change in track density as the particle slows down and stops near the center of the chamber.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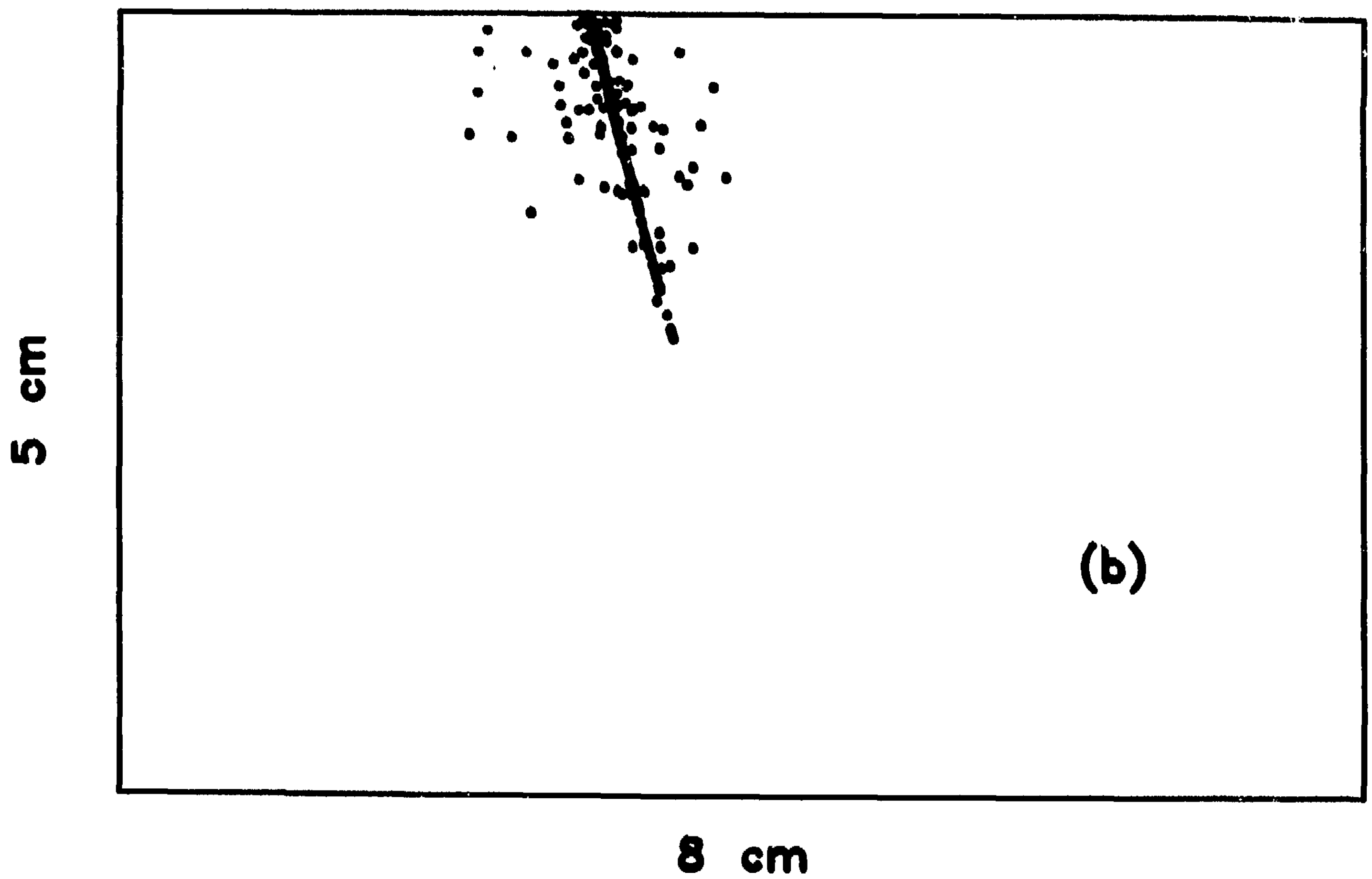
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